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YUCHE CHEN, University of Nebraska Omaha, Omaha, NE, United States

XIAOYUE CHENG, University of Nebraska Omaha, Omaha, NE, United States

RICH KNEPPER, Cornell University, Ithaca, NY, United States

Open Access Support provided by:

University of Nebraska Omaha

Cornell University

Published: 18 December 2025

Online AM: 09 October 2025

Accepted: 01 June 2025

Revised: 22 January 2025

Received: 11 May 2023

[Citation in BibTeX format](#)

Effective Digital Government Platforms: Advanced Computing Cyberinfrastructure for Scientific Innovations

YU-CHE CHEN, School of Public Administration, University of Nebraska at Omaha, Omaha, United States
XIAOYUE CHENG, Department of Mathematical and Statistical Sciences, University of Nebraska at Omaha, Omaha, United States
RICHARD KNEPPER, Cornell University, Ithaca, United States

The existing literature on digital government lacks a rigorous empirical investigation into advanced computing cyberinfrastructure for scientific innovation. Distributed computing cyberinfrastructures are an increasingly salient form of digital platform government enabling service production and delivery. Government cyberinfrastructure programs for scientific innovation advance national competitiveness. This study draws from the literature on digital government, cyberinfrastructure, and socio-materiality to develop hypotheses on the effectiveness of cyberinfrastructure as a platform government. The US NSF cyberinfrastructure program, the largest government-funded digital platform for scientific innovation, is the focus of the empirical investigation in this article. The results from the selected scientific fields in this program support the importance of equity effort, capacity, and socio-material coupling for effectiveness. The variations in the relative impacts of these factors imply the need to have a targeted field-specific strategy rather than a generic one across fields of science. The empirical findings suggest the calibration of the type of equity effort, the level at which capacity resides, and the scale and type of socio-material coupling for effectiveness.

CCS Concepts: • **Social and professional topics** → **Government technology policy**;

Additional Key Words and Phrases: Digital government, platform government, cyberinfrastructure, scientific innovations

ACM Reference Format:

Yu-Che Chen, Xiaoyue Cheng, and Richard Knepper. 2025. Effective Digital Government Platforms: Advanced Computing Cyberinfrastructure for Scientific Innovations. *Digit. Gov. Res. Pract.* 6, 4, Article 47 (December 2025), 20 pages. <https://doi.org/10.1145/3745788>

1 Introduction

The digital government literature reveals a growing recognition of the centrality of public values to guide and measure the development of digital government [23, 49]. Government, in comparison with business and nonprofit organizations, has a public mission to serve society. The capabilities of digital technologies enable governments to offer integrated and personalized e-government services [21, 28] in order to advance public values, such as

This project is supported in part by the NSF Award Number: 2346631.

Authors' Contact Information: Yu-Che Chen (corresponding_author), School of Public Administration, University of Nebraska at Omaha, Omaha, Nebraska, United States; e-mail: ychen@unomaha.edu; Xiaoyue Cheng, Department of Mathematical and Statistical Sciences, University of Nebraska at Omaha, Omaha, Nebraska, United States; e-mail: xycheng@unomaha.edu; Richard Knepper, Cornell University, Ithaca, New York, United States, e-mail: rich.knepper@cornell.edu.



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ACM 2639-0175/2025/12-ART47

<https://doi.org/10.1145/3745788>

efficiency, effectiveness, equality, accountability, and responsiveness [43]. Among these public values, effectiveness and efficiency have been central to the study of digital government [50]. The organizational and institutional characteristics of governments determine the specific digital technologies adopted and their effectiveness [2, 21].

Platform government that leverages digital technology to connect organizations and people for public policy and service constitutes a growth area of digital government [28, 33]. Platform government and blockchain-based services are examples of utilizing collaborative digital innovations connecting organizations and facilities for the provision of government information and services for public value creation [28, 57]. The existing scholarship platform government has articulated the need for and value of combining technological and organizational innovations for cross-boundary collaboration in public service production and delivery. However, empirical studies on what makes platform government effective lag behind the practice.

Moreover, digital government is about achieving the missions of government agencies by leveraging technological innovations in a complex context [16, 23, 31]. One such mission is to achieve national competitiveness in science and technology. A recent example is in the area of artificial intelligence, where governments have developed strategies to propel national competitiveness [47]. High-performance computing is regarded as a central capability for scientific and technological competitiveness [4, 45]. The **United States National Science Foundation (US NSF)** cyberinfrastructure program, which began in 2004, is an important government effort toward the production and delivery of high-performance computing via cyberinfrastructure [66]. The most recent NSF-funded national research cyberinfrastructure program with an investment of \$52 million from 2023 to 2027 highlights the critical role of such infrastructure in ensuring US leadership and economic competitiveness [1]. The existing digital government literature has explored the utilization of digital technologies for public service, open government, and collaborative governance. However, less is known about digital government policies and programs geared toward national competitiveness in science and technology in general and the role of advanced computing cyberinfrastructure as a form of platform government in particular.

This study aims at contributing to the digital government scholarship by examining cyberinfrastructure as a salient and emerging platform for the production and delivery of digital government services. Moreover, it aims at addressing the government's mission to advance scientific and technological innovation via the use of cyberinfrastructure as a form of platform government. The primary public value associated with digital government is effectiveness. This study, therefore, poses the following research question: what are the factors affecting the effectiveness of cyberinfrastructure as a digital government platform? This study integrates insights from digital government, platform government cyberinfrastructure, and social materiality. This study's empirical basis is the US NSF's cyberinfrastructure program, which is a government platform that provides high-performance computing services for scientific innovations. This setting embodies key characteristics of digital platform government, including cross-boundary collaboration, distributed computing, and public values.

This article first contextualizes cyberinfrastructure as a platform form of digital government. It follows with the development of a conceptual framework for the main factors affecting the effectiveness of advanced computing cyberinfrastructure and the ensuing research hypotheses. This article then describes the data and methods for testing research hypotheses. Next is the presentation of the results, followed by their interpretations and implications for theory and practice. This article concludes with a summary, limitations of the study, and suggestions for future research.

2 Collaborative Digital Government Platforms for Public Value Creation

2.1 Digital Government Platforms: Cyberinfrastructure for Scientific Innovations

Digital government platforms are government platforms that leverage digital information and communication technologies for public value creation. Platform government has emerged as the result of rapid development in connected information and communication technologies and computational data analytic capabilities [33]. Digital innovations powering platform government hold the potential of transforming bureaucratic government and

public management for collaborative public value creation [33, 40]. Government platforms, compared with the traditional hierarchical form of government, emphasize openness, transparency, cross-boundary collaboration, and ecosystem-like relationships [15, 25, 28].

Digital government platforms leverage digital information and communication technologies to facilitate and enhance collaboration for public value creation, such as efficiency and effectiveness. Technologies such as social media, blockchain, artificial intelligence, and distributed computing to create value for the stakeholders of digital government. These digital government platforms can strengthen intergovernmental collaboration as well as the interaction and collaboration among citizens, businesses, nonprofit organizations, and governmental agencies [22, 28, 41]. Citizen service platforms such as 311 systems in major U.S. cities provide technology-enabled interactions between government and citizens to create more efficient and effective government services [54]. These digital platforms can prove effective in different public service areas, such as information sharing using blockchain and the production and delivery of computing resources for scientific research, such as the open science grid [5, 57].

Government cyberinfrastructure for advanced computing services has the key features of digital government platforms. Cyberinfrastructure is composed of "computational systems, data and information management, advanced instruments, visualization environments, and people, all linked together by software and advanced networks to improve scholarly productivity and enable knowledge breakthroughs and discoveries not otherwise possible" [56]. On the technology side, cyberinfrastructure "integrates hardware for computing, data and networks, digitally-enabled sensors, observatories and experimental facilities, and an interoperable suite of software and middle-ware services and tools" [44]. Such integration reflects digital technological innovation to connect various software and hardware across geographically dispersed entities to support the production and delivery of a service. On the organizational side, cyberinfrastructure has a distributed architecture of inter-organizational collaboration that is open and adaptable to complex relationships. Overall, cyberinfrastructure exemplifies the integration seen in digital government platforms by orchestrating the coupling of computing, networking, and human systems [55].

Moreover, cyberinfrastructure for advanced computing is an increasingly salient service empowering technological innovation for digital government. Such advanced capabilities help accelerate scientific innovations, which increasingly rely on advanced computing power [20]. Artificial intelligence is a case of reliance on advanced computing capabilities. The development of artificial intelligence is also central to the next phase of digital government innovations [3].

2.2 Effectiveness as a Central Public Value

Effectiveness is one of the central public values of digital government [50]. Effectiveness concerns the extent to which a goal or objective is achieved [27, 53]. For government policies and programs, effectiveness is an inclusive value that embodies goals such as responsiveness to citizens and protection of digital privacy. A systematic literature review of digital government reveals that effectiveness and efficiency are two prominent public values studied in this field. Recent work on artificial intelligence also refers to effectiveness as one of the core public values to measure against [50, 65].

The effectiveness of digital platform government depends on the public service goal established for the government platforms. For instance, for open government initiatives relying on digital government data platforms, effectiveness can be measured by the level of interoperability among the participating government agencies in providing government data to the public [51]. For digital platforms powering scientific innovation, a measure of effectiveness is the integration of dispersed computing resources to provide personalized and responsive advanced computing support for scientific research [5].

The effectiveness of the cyberinfrastructure for scientific innovations can be measured by the outcome. The main public service output of cyberinfrastructure for scientific innovations is the amount of computing resources

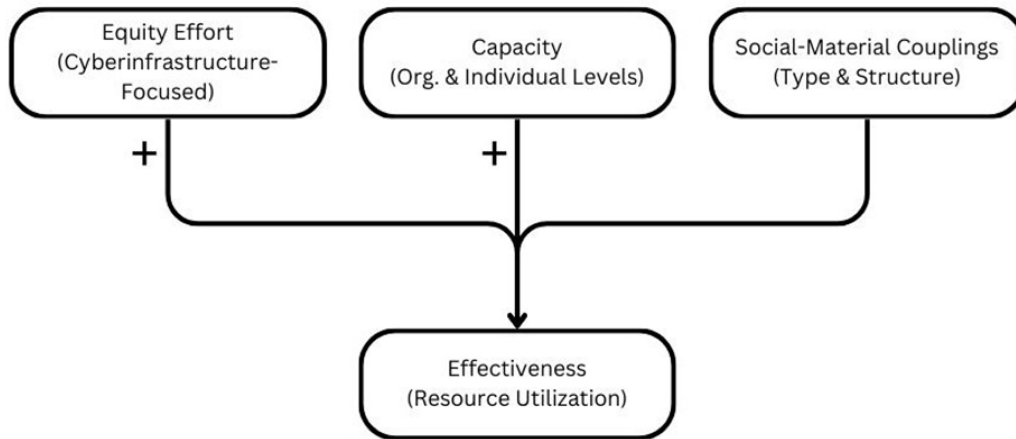


Fig. 1. A Conceptual framework for the effectiveness of cyberinfrastructure as a digital government platform.

made available to researchers and project investigators. The primary direct outcome of cyberinfrastructure is the actual utilization of these computing resources, recognizing the gap between allocation and utilization of computing resources.

2.3 Factors for Effective Cyberinfrastructure as a Digital Government Platform for Advanced Computing Services

This section develops a conceptual framework for considering the effectiveness of advanced computing cyberinfrastructure as a digital government platform. This study draws from previous studies on digital government, platform government, cyberinfrastructure, and socio-materiality to answer the research question. The existing digital government literature informs the factors for digital government success, particularly in public value creation. The platform government literature, including studies on network forms of governments, informs the consideration of entities of multiple levels. Studies on cyberinfrastructure offer insights into the effective design and implementation of this type of digital government platform. Finally, the socio-materiality literature highlights the role of computers and the coupling of the socio and materials. Figure 1 summarizes the key conceptual constructs and their hypothesized relationships with effectiveness based on the literature review.

2.3.1 Equity Effort. Equity efforts play an important role in realizing the effectiveness of government policies and programs. Due to their public mission, government policies and programs often seek to address the needs of disadvantaged groups. As a result, equity effort contributes directly to the effectiveness of achieving equity-driven goals. For instance, the US broadband infrastructure programs, such as the ones supported by the Digital Equity Act, aim at addressing the digital divide in broadband access in underserved communities. Efforts at identifying, engaging, and building broadband infrastructure for these rural communities increase the effectiveness of this program.

Cross-boundary collaboration and integration via the use of information and communication technologies are important equity efforts for digital platform government. The integration of resources across geographically dispersed and diverse organizations builds the resource base. Such integration effort can take the form of building capacity for joint action, standardization of data, interoperability, and inter-organizational trust [11, 13]. The customized distribution of integrated resources relies on activities to bridge the gap between the resources that cyberinfrastructure as a digital government platform can provide and the capabilities of disadvantaged organizations and individuals to access such resources [32].

For cyberinfrastructure as a digital government platform, equity efforts aim at providing greater access and utilization of cyberinfrastructure by organizations and individuals that would not have access to such resources otherwise [64]. The foundational effort of cyberinfrastructure requires the building of software systems to integrate computing resources across organizations and computers [12]. Once the integration of distributed computing resources is established, targeted outreach and technical support for disadvantaged organizations and individuals can address the challenge of these organizations and individuals in accessing the integrated resource base [32]. These bridging equity efforts are likely to increase the effectiveness of cyberinfrastructure in terms of utilization by disadvantaged organizations and individuals. Therefore, pose the following hypothesis:

H1: Equity effort is positively associated with the effectiveness of cyberinfrastructure as a digital government platform.

2.3.2 Capacity Building. Capacity matters in effective inter-organizational collaboration in digital government service [6, 13, 24, 49]. In this context, capacity includes both technical and organizational capabilities. Technical capacity refers to the development and utilization of information and communication technologies for inter-organizational communication and coordination [11, 24]. For instance, technological knowledge and skills can improve service quality in an inter-organizational setting for open government data [58]. Organizational capacity entails the ability to create and sustain shared goals and to take joint actions across varying organizational priorities and circumstances to accomplish these goals [13, 19].

Capacity resides in both organizational and individual levels. Organizational innovativeness is an important factor for a government agency's adoption and implementation of digital government initiatives [42, 61]. An innovative culture enables the development of both technical and organizational capacities needed for inter-organizational collaboration. Resources are another important organizational factor for capacity. A resource-rich organization can afford the investment in technology, time, and staff to contribute to effective inter-organizational collaboration [62]. At the individual level, the relevant capacities include knowledge and skills to contribute to the operation and development of inter-organizational collaboration and the capability to leverage the resources of such collaboration [13].

An analytical understanding of cyberinfrastructure as a digital government platform requires discernment of two levels (organizations and individuals) and two types of capacity (technical and organizational). At the organizational level, technical and organizational capacities for engaging in distributed collaboration across geographical and organizational boundaries could reside in an office providing organization-level support for the participating individuals and units inside the organization. For government-sponsored cyberinfrastructure projects, a university's office of sponsored projects can provide support in navigating the rules and regulations of government funding agencies to develop and implement accountable proposals. This office can assist in developing governance capacities such as project management, institutional review, and privacy and regulatory compliance assistance. In addition, this office could foster collaborative ties that extend across and outside of the university and permit entrepreneurial initiatives that develop industry relations and manage intellectual property resulting from research [37]. Moreover, organizational technical capacity for cyberinfrastructure for high-performance research computing involves an organization-level unit for advanced computing. Such an advanced computing unit such as a university center, can serve as the main technical resource for individuals or teams accessing the resources available in the inter-organizational cyberinfrastructure.

At the individual level, the researchers utilizing cyberinfrastructure resources need to possess both technical and administrative capacities. A key technical capacity is computational thinking, which supports the use of computational methods to support research inquiry [63]. Given the fluidity of cyberinfrastructure resources, another key technical capacity is the ability to adapt to changing resources and minimize transition costs incurred from moving to new resources [34]. Administrative capacity refers to the knowledge and skills necessary to conduct practices that are conducive to the utilization of cyberinfrastructure resources. The related abilities include setting shared goals and productive routines, developing and executing administrative and computational

workflows, seeking multidisciplinary expertise, collaborating with research software engineers, and engaging with bridging liaisons [17, 32].

The importance of technical and organizational capacity for utilizing cyberinfrastructure resources provides support for the following hypothesis:

H2: Capacity is positively associated with the effectiveness of cyberinfrastructure as a digital government platform.

2.3.3 Socio-material Coupling. Materials such as tools, documents, and concepts play an important role in a network form of organization, as exemplified in cyberinfrastructure as a form of digital platform government [9, 14]. The actor-network theory further acknowledges non-human objects as actors in a network [36]. These non-human objects include routines, experiments, measurements, instruments, and texts. Furthermore, these non-human objects underpin the technological capabilities of a network form of a technology-enabled modern organization. As a result, a rigorous analysis of cyberinfrastructure as a digital government platform should explicitly include materials in the analysis of the relationships among key entities.

The coupling of social and material represents the essence of interactions in an organization and is likely to be prominent in digital government platforms that connect software, hardware, and people together [9, 48]. Such interactions emphasize both the social and material aspects of technology and organization and the importance of coupling the two [48]. Social-materiality theory adopts a relational understanding of the social and material and underscores the coupling of the social and material [9]. Through the lens of social materiality, the relationship between technology and organizational activities should be central to understanding cyberinfrastructure as a digital government platform.

Materials play a prominent role in cyberinfrastructure for digital government research computing services. These materials include computers with advanced computing capabilities, workflows and routines for the production and delivery of computing resources, and the telecommunication network to deliver the resources to the targeted organization. For instance, in the early development of cyberinfrastructure for scientific research, 13 resource institutions offered their super-computer and networking capabilities to serve various organizations and research teams across the nation [46]. These computing resources play an important role in accelerating the development of cyberinfrastructure for innovations.

The coupling of social and material is evident in the development and implementation of governance systems and software models for the creation of cyberinfrastructure to integrate computing resources in a distributed environment. The execution policies and production systems underpinning the coupling of social and material affect even the containerized application of cyberinfrastructure [60]. The coupling of social and material can take the form of the number and type of resources utilized in a grant project led by a PI working in an institution. A stronger coupling will have a higher number, larger size, and broader extension of resources utilized by a PI. Such couplings bring together differing hardware, operating systems, software, and middleware implementations to provide integrated computing support services [32]. For instance, the TeraGrid program integrates organizations, computing architecture, and software to provide computing resources for researchers to conduct new computing-intensive inquiries that are otherwise not available to these researchers [8]. Therefore, socio-material coupling is likely to be associated with a higher level of effectiveness measured by the level of utilization.

H3: The coupling of social and material is positively associated with the effectiveness of cyberinfrastructure as a digital government platform.

3 Data and Methods

3.1 US NSF's Cyberinfrastructure Program and Fields of Science

This study focuses on US NSF's cyberinfrastructure program as a digital government platform due to its public mission, size, and impact. The NSF cyberinfrastructure program aims at providing publicly funded advanced

computing services to researchers in the United States. This program has a history of over 15 years, from Tera-Grid to **Extreme Science and Engineering Discovery Environment (XSEDE)** 1 and 2, with a total resource investment of over \$270 million. Based on an analysis of the NSF cyberinfrastructure award data by the authors, this program has helped support access to and utilization of advanced computing resources under more than 19,000 projects; 8,000 principal investigators; and 150 fields of science. These projects include major discoveries and applications, such as earthquake prediction and powering e-decision systems to keep K-12 students safe [64].¹

This NSF-funded cyberinfrastructure program emphasizes providing support to institutions and individual researchers with limited or no access to advanced computing resources. The main programmatic activity to improve access is the implementation of the Campus Champion program [38]. The Campus Champion program is intended to help researchers navigate the rapidly changing technological environment and identify and use resources that help their basic research aims. The champions are volunteers charged with promoting effective participation in the national cyberinfrastructure environment. One or more champions may be at a given institution and provide its researchers with guidance and expertise on using national cyberinfrastructure resources. Champions are provided workforce development opportunities, training, and a network of similar-minded individuals to help coordinate activities. Moreover, champions participate in monthly calls on a range of topics of interest to the research computing and data community, engage in peer mentorship, build a community of practice, and use the Practice and Experience in Advanced Research Computing (PEARC) conference as an annual meeting.

This study examines the hypothesized relationships within different scientific fields. Previous exploratory work at the level of the cyberinfrastructure program has demonstrated the relevance of structural and organizational factors as well as the relational nature of socio-material coupling [10]. This study advances understanding by examining the effectiveness of cyberinfrastructure as a digital government platform at the level of individual fields of science that typically have unique needs and approaches to the utilization of cyberinfrastructure. This broad focus on the field of science promotes theoretical advances by testing the three hypotheses mentioned and exploring the variations in fields of science. In addition, the focus on fields of science explores the relevance and value of providing field-specific recommendations for practices of cyberinfrastructure as a digital government platform.

The selection of the scientific fields aims at capturing the diversity in the utilization of cyberinfrastructure resources and approaches to cyberinfrastructure use. The three fields of science selected are chemistry, genetics and nucleic acids, and advanced scientific computing. These fields represent the range of high (chemistry), medium (genetics and nucleic acids), and low (advanced scientific computing) usage of computing resources provided by cyberinfrastructure on a per-grant basis. Moreover, these fields vary in their maturity and variability in utilizing cyberinfrastructure resources.

Chemistry projects are a traditional area of inquiry supported by computational research, including the modeling and simulation of chemical processes, calculation of chemical reactions, and visualization of chemical bonds and changes. This field has long been part of computational research, and there is a set of software packages that are in general use. While some computational chemists develop their own software, most are able to meet their needs with existing software. Genetics is one area of computational analysis that has grown significantly over the time period observed in this study. The growth of computational techniques in biology is associated with the evolution of the numerical representation of genetic data. Improved techniques for capturing and sequencing data have revolutionized genetic research [26]. Computing research is the first use case of computational research and includes the development of algorithms that support research in other domains of science. Computing research is frequently focused on the development and improvement of modeling, mathematical techniques for analysis, or distributed computing techniques.

¹<https://www.xsede.org/-/san-diego-supercomputer-center-researchers-help-keep-k-12-students-covid-safe> accessed January 18, 2022.

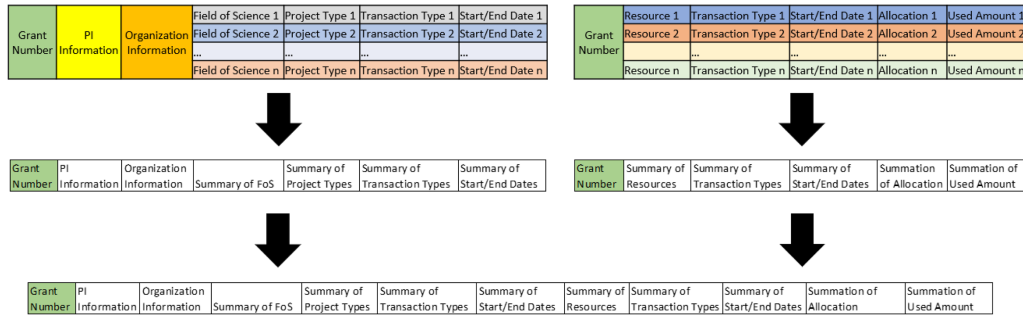


Fig. 2. Organization and aggregation of data.

3.2 Research Data and Operationalization of Variables

This study draws from a unique data set compiled by the researchers with a focus on universities and colleges as well as the selected scientific fields. This data set combines four data sources to test the three hypotheses proposed in the study. The first is the XSEDE data set, which provides information about the project awards. Each record includes the grant number, name of the **principal investigator (PI)**, the PI's organization, the scientific field, project type, transaction type, project title and abstract, and start and end date. The second source is the allocation and utilization of computing resources from the project awards. Each record contains the grant number, computing resource name, transaction type, initial allocation, final allocation, used amount, and start and end date. The third data source is the Carnegie classification of institutes of higher education, which contains the classification codes for 4,324 institutes in the United States, of which only 416 organizations can be directly matched with the XSEDE data. The last data set is the Campus Champion data set, which lists the participating institutions and the date when a campus champion was established for the institution.

In order to aggregate and merge data records from various data sources, the unit of analysis is the grant. Figure 2 illustrates the process of data aggregation and merging. This unit captures the organization of the research effort, where the focus is on a unique principal investigator from an associated scientific field. Moreover, this unit of analysis reflects the essential aspects of cyberinfrastructure resource utilization, including the type and amount of resource allocation, type of transaction, and duration (typically several years).

3.2.1 Operationalization. The dependent variable cyberinfrastructure service effectiveness in this study is operationalized as use amount. The use of computing resources for scientific innovation is the primary goal of cyberinfrastructure services. The use amount is measured by the number of computing service units consumed. Each unit is a normalized core hour based on a reference processor. The variable that counts the number of core-hours is a ratio one. For a grant project, the total utilization is the aggregate number of service units consumed by the project through running jobs that potentially draw from various processors for a significant number of hours. This operationalization allows for exact accounts of the computing resources utilized by specific grants as well as a meaningful comparison of utilization across grants. Table 1 presents the variables organized around the main constructs, data type, and definition/operationalization. The description below focuses on the variables that register a statistically significant relationship with the dependent variable for any of the three selected scientific fields.

For equity effort, we focus on two types of champion efforts in the context of the NSF cyberinfrastructure program. The first type concerns the existence and history of campus champions and their impacts on utilization. The first measure of this type is whether an institution had a campus champion at least two years before the start year of the grant: *ChampionBefore*. The two-year cut-off accounts for the typical lead time of one year or longer needed for review and approval of the grant and subsequent application of resources prior to utilization.

Table 1. Operationalization of Variables

Concept	Dependent Variable	Data Type	Definition/ Operationalization
Effectiveness	Used_Amount	Numeric	The aggregate amount of allocation units used on the resource by the grant.
Concept	Independent Variable	Data Type	Definition/ Operationalization
Equity Effort	ChampionBefore	Logical (1 = Yes, 0 = No)	Whether the organization had any Campus Champions at least two years before the start year of this grant.
	ChampionNow	Logical (1 = Yes, 0 = No)	Whether the organization had any other Campus Champions only one year before the start year of this grant, or in the same year but before the start date of this grant.
	isChampion	Logical (1 = Yes, 0 = No)	Whether this grant contains any award of which the project type is Campus Champion.
Capacity	PI_New	Logical (1 = Yes, 0 = No)	Whether the same PI had any previous grant before the start date of this grant.
	PI_PrevUsage	Numeric	Total used amount of previous grants from the same PI.
	PI_PrevUsageRate	Numeric	Median of usage rate of previous grants from the same PI.
	Org_New	Logical (1 = Yes, 0 = No)	Whether the same organization had any previous grant before the start date of this grant.
	Org_PrevFoS	Integer	Number of unique fields of science from the same organization that received NSF awards prior to this grant.
	Org_PrevUsage	Numeric	Total used amount of previous grants from the same organization.
	Org_PrevUsageRate	Numeric	Median of usage rate of previous grants from the same organization.
	Carnegie15	Logical (1 = Yes, 0 = No)	Whether the organization is of category 15 of the Carnegie classification (Doctoral Universities: Very High Research Activity).
Social-material Coupling	Count_Resource	Integer	Number of unique computing resources the grant number used.
	Type_LRAC	Logical (1 = Yes, 0 = No)	Whether this grant contains any award of which the project type is LRAC (large allocation).
	Type_MRAC	Logical (1 = Yes, 0 = No)	Whether this grant contains any award of which the project type is MRAC (medium allocation).
	Type_XRAC	Logical (1 = Yes, 0 = No)	Whether this grant contains any award of which the project type is XRAC (XSEDE Research Allocations Committee).
	Type_DAC	Logical (1 = Yes, 0 = No)	Whether this grant contains any award of which the project type is DAC ("Development Allocation" under TeraGrid, one of DAC-Kraken, DAC-NCSA, DAC-PSC, DAC-Ranger, DAC-SDSC, and DAC-TG)
	Transaction_new_usage	Logical (1 = Yes, 0 = No)	Whether this grant contains any usage record of which the transaction type is New.
	Transaction_renewal_usage	Logical (1 = Yes, 0 = No)	Whether this grant contains any usage record of which the transaction type is Renewal.
	Transaction_advance	Logical (1 = Yes, 0 = No)	Whether this grant contains any usage record of which the transaction type is Advance.
	Transaction_supplement	Logical (1 = Yes, 0 = No)	Whether this grant contains any usage record of which the transaction type is Supplement.
Control	Initial_Allocation	Numeric	Total initial allocation of a grant.
	Type_Startup	Logical (1 = Yes, 0 = No)	Whether this grant contains any award of which the project type is Startup.
	Type_Research	Logical (1 = Yes, 0 = No)	Whether this grant contains any award of which the project type is Research.
	Type_Discretionary	Logical (1 = Yes, 0 = No)	Whether this grant contains any award of which the project type is Discretionary.
	Count_Project	Integer	Number of awards the same grant number has.
	Count_FoS	Integer	Number of unique fields of science the grant number covers.

The second measure of this type is whether the organization had any campus champions one year before the start year of the grant or in the same year but before the start date of this grant (ChampionNow). The second type of effort is an allocation of computing resources in support of campus champions, determined by whether the grant contains any award of which the project type is Campus Champion (IsChampion). The allocation of computing resources to support the campus champion program indicates direct resource support.

For capacity, the eight independent variables are grouped into the individual (principal investigator, PI) and organizational (university) levels in order to discern the influence of capacity at different levels over utilization. At the PI level, there is one dichotomous variable, which measures whether the PI has no prior grant award from the cyberinfrastructure program (PI_New), indicating a lack of capacity. Another variable is the amount of computing resources from the cyberinfrastructure program used by the PI prior to the grant (PI_PrevUsage). The amount of previous usage is a proxy for the capacity of the PI to utilize computing resources successfully. At the organizational level, there are several key capacity variables. First is a dichotomous variable capturing whether the institution as a whole has no prior usage of cyberinfrastructure resources (Org_New). No prior usage indicates that the institution has no experience working with the NSF cyberinfrastructure program. Another key variable is whether the institution is classified as a doctoral university with very high research activity by the Carnegie classification of universities and colleges (Carnegie 15). This rank indicates that the university has a substantial number of doctoral programs with a high level of research activities, which serves as an indication of research capacity that is conducive to the utilization of cyberinfrastructure resources.

For social material coupling, there are measures of both the quantity and quality of couplings. The measure of the quantity of coupling is the number of computing resources utilized (Count_Resource). The more computing resources utilized by a particular grant, the larger the number of couplings between its research team and the computing resources made available via the cyberinfrastructure. A larger number of couplings is likely to be associated with a larger total amount of utilization. The measures of the quality of coupling include two subcategories. First is the classification of grant project types as **medium resource allocation classification (MRAC)**, **large resource allocation classification (LRAC)**, **extreme resource allocation classification (XRAC)**, or **discretionary allocation classification (DAC)**. The large or extreme allocation classification indicates that a project is connected with large or extreme numbers of computing resources. Therefore, such a classification is likely to be associated with a larger amount of utilization. The second subcategory concerns the types of transactions (new, renewal, advance, and supplement). The new transaction indicates a new coupling with a steep learning curve for utilization. Renewal and supplemental transactions indicate the extension of an existing coupling, which is likely to propel more utilization than in the case of new transactions.

Moreover, this study also introduces several variables that are highly correlated with the use amount to exercise statistical control in this multivariable framework of analysis. These variables include the initial allocation of computing resources, the type of resource awards (start-up, research, and discretionary), and the number of resource awards.

3.3 Descriptive Statistics and Model Selection

Table 2 presents the descriptive statistics of all of the variables. All three scientific fields are included because their statistics vary. Most of the variables are dichotomous, indicating whether a given effort, capacity, or social material coupling is present for a particular grant, as described in Table 1. For these dichotomous variables, the means suggest the percentage of the grants that have a certain factor present. The means and standard deviations for the numeric variables allow for comparison across the scientific fields.

This study employs a Tweedie **generalized linear model (GLM)** that is appropriate for our data. Generalized linear models are suitable for distributions of dependent variables that are not normal. Generalized linear models are also more effective for addressing multicollinearity. The distribution of the dependent variable for this study is continuous, non-negative, right-skewed, and zero-inflated. Tweedie distributions are well matched to these

Table 2 Selected Descriptive Statistics for Three Fields of Science

Field of Sciences		Chemistry		Genetics and Nucleic Acid		Advanced Scientific Computing	
Concept	Variable	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
Equity Effort	ChampionBefore	0.1891	0.3919	0.3393	0.4743	0.1843	0.3882
	ChampionNow	0.2617	0.4398	0.5179	0.5006	0.2466	0.4316
	isChampion	0.0078	0.0879	0.0000	0.0000	0.0705	0.2563
Capacity	PI_New	0.6477	0.4780	0.8929	0.3098	0.6721	0.4701
	PI_PrevUsage	977050.9336	9420265.1956	22460.2080	172995.0577	247414.5983	2206968.0323
	PI_PrevUsageRate	0.3636	1.0881	0.0629	0.2291	0.2373	1.2510
	Org_New	0.1205	0.3257	0.0643	0.2457	0.1247	0.3308
	Org_PrevFoS	12.8148	16.1327	22.0214	19.7912	13.6450	17.3234
	Org_PrevUsage	69815596.0761	142988111.8908	102511513.5500	150876872.4611	79916345.9241	158134025.5789
	Org_PrevUsageRate	0.5305	0.4855	0.4416	0.3005	0.4030	0.3384
	Carnegie15	0.6645	0.4725	0.6893	0.4636	0.6450	0.4792
Social-material Coupling	Count_Resource	2.8355	2.5024	2.4607	1.7936	3.8482	5.4207
	Type_LRAC	0.0013	0.0360	0.0000	0.0000	0.0027	0.0521
	Type_MRAC	0.0091	0.0949	0.0036	0.0598	0.0054	0.0735
	Type_XRAC	0.0674	0.2508	0.0464	0.2108	0.0407	0.1977
	Type_DAC	0.0117	0.1074	0.0143	0.1189	0.0000	0.0000
	Transaction_new_usage	0.9443	0.2295	0.9893	0.1031	0.9539	0.2099
	Transaction_renewal_usage	0.2798	0.4492	0.1107	0.3143	0.2520	0.4348
	Transaction_advance	0.0557	0.2295	0.0286	0.1669	0.0190	0.1366
	Transaction_supplement	0.0855	0.2798	0.0607	0.2392	0.1247	0.3308
Control	Initial_Allocation	288372.7235	664006.9720	99650.4258	143435.4558	290533.0253	678006.3689
	Type_Startup	0.4598	0.4987	0.8857	0.3187	0.4363	0.4966
	Type_Research	0.1218	0.3272	0.0714	0.2580	0.0650	0.2469
	Type_Discretionary	0.0026	0.0509	0.0000	0.0000	0.0000	0.0000
	Count_Project	1.5194	1.1104	1.1786	0.5391	1.5068	1.4373
	Count_FoS	1.1321	0.3854	1.0857	0.2929	1.1789	0.4490
Effectiveness	Used_Amount	209143.7487	483251.0453	48666.5933	71047.7808	106678.797	332671.27

distributional characteristics of the dependent variable [30, 59]. This study utilized the R package Tweedie and Statmod to conduct the Tweedie GLM via their numerical algorithms [18, 39]. This study employs one model for each of the selected scientific fields: chemistry, genetics and nucleic acids, and advanced scientific computing. McFadden's Pseudo R-squared is the basis for the model assessment and comparison of the explanatory power of the different models [39].

4 Results of GLM Models

The results of the Tweedie GLM are summarized in Tables 3 and 4. Table 3 presents the information on the three full models. Table 4 focuses on the statistically significant results. The variables are organized around the key categories that align with the three main hypotheses. This section begins with a field-specific report on the results. It then reports the collective results of all three models as relevant to the three hypotheses. Given that the results are from the multivariate analysis, the statistical association reported is after controlling for all other variables.

Table 3 The Results of the Full Tweedie GLS Models

	Chemistry	Genetics and Nucleic Acid	Advanced Scientific Computing
(Intercept)	1.06E+01***	1.05E+01***	1.07E+01***
Equity Effort			
ChampionsBefore	4.59E-01***	−9.33E-02	−2.89E-01
ChampionsNow	−1.49E-01	−7.94E-02	1.59E-01
isChampion	−1.93E+00**	NA	1.35E+00*
Capacity			
PI_New	−3.08E-01*	−5.88E-01	−2.70E-01
PI_PrevUsage	1.23E-08***	5.80E-07	1.07E-08
PI_PrevUsageRate	−2.50E-02	−4.78E-01	−1.53E-01
Org_New	2.08E-01	−3.27E-02	−1.00E+00*
Org_PrevFoS	−1.30E-04	8.87E-03	4.36E-03
Org_PrevUsage	−8.25E-10	−2.18E-10	−2.01E-10
Org_PrevUsageRate	1.69E-01	4.69E-01	−3.47E-01
Carnegie15	1.87E-01	7.09E-02	9.13E-01***
Social-material coupling			
count_Resource	4.83E-02*	−9.36E-03	−1.51E-01***
Type_LRAC	1.88E+00***	NA	1.35E-01
Type_MRAC	4.41E-01	−1.01E+00	1.69E+00*
Type_XRAC	3.65E-01**	6.10E-01	1.56E+00***
Type_DAC	−1.18E+00	−5.53E-01	NA
Transaction_new_usage	2.35E-01	2.89E-01	−9.41E-01*
Transaction_renewal_usage	7.88E-01***	7.48E-01	4.06E-01
Transaction_advance	3.20E-02	2.80E-01	−1.98E+00**
Transaction_supplement	2.92E-01*	8.09E-01**	1.09E+00***
Control			
Initial_Allocation	4.67E-07***	2.11E-06***	1.06E-06***
Type_Startup	−2.47E-01	3.70E-01	5.64E-01*
Type_Research	6.32E-01***	3.10E-01	1.65E+00***
Type_Discretionary	8.22E-01	NA	NA
count_Project	3.38E-02	−2.51E-01	6.89E-02
count_FoS	6.39E-02	−4.04E-01	−7.65E-02
Number of Observations	772	280	369
McFadden's pseudo r-squared	0.6917988	0.285249	0.663056

Note: *p < 0.05, **p < 0.01, ***p < 0.001.

For chemistry, there is partial support for Hypothesis 1, which predicts a positive relationship between equity effort and effectiveness. More specifically, the Campus Champion effort prior to the current grant exhibits a positive and statistically significant relationship with the use amount. Interestingly, the allocation of Campus Champion computing resources bears a negative association with the use amount. For capacity, there is support for Hypothesis 2 that capacity is positively associated with effectiveness. A PI's lack of experience is an indication of a lack of capacity. Consistent with the hypothesized relationship, lack of experience is negatively associated with use amount. In addition, previous use—an indication of capacity for utilizing cyberinfrastructure resources—exhibits a statistically significant positive association with use amount.

Table 4. Summary of the Tweedie Models for Three Fields of Science

	Chemistry	Genetics and Nucleic Acid	Advanced Scientific Computing
Equity effort			
ChampionBefore	(+) ^{***}		
ChampionNow			
isChampion	(-) ^{**}		(+) [*]
Capacity			
PI level (experience and usage)	PI_New (-) [*] PI Previous usage (+) ^{***}		
Org level (experience and research capacity)			Org_New (-) [*] Carnegie15 (+) ^{***}
Social-material couplings			
Number of resources used	(+) [*]		(-) ^{***}
Types of resource allocations (LRAC, MRAC, XRAC, DACT)	LARC (+) ^{***} ; XRAC (+) ^{**}		MRAC (+) [*] ; XRAC (+) ^{***}
Transaction types (new, renewal, advance, and supplement)	Renewal use (+) ^{***} Supplemental (+) [*]	Supplemental (+) ^{**}	New usage (-) [*] Advance (-) ^{**} Supplemental (+) ^{***}
Control			
Initial allocation	(+) ^{***}	(+) ^{***}	(+) ^{***}
Type of awards (start up, research, discretionary)	Research (+) ^{***}		Start up (+) [*] Research (+) ^{***}

Note: This table focuses on statistically significant relationships.

There is also support for Hypothesis 3 under chemistry, suggesting that socio-material couplings influence effectiveness. More specifically, the number of resources used is positively associated with the use amount. The type of resource allocation, which indicates the scale of coupling, also demonstrates a statistically significant positive relationship with use amount, particularly in the case of large allocation classifications (large and extreme). In addition, the transaction type, which reflects the nature of the coupling, exhibits a significant relationship with use amount. More specifically, the renewal type and supplemental type demonstrate such a relationship.

For genetics and nucleic acids, no statistically significant relationship was found to support any of the three hypotheses. Only the initial allocation amount, a control variable, exhibits a significant relationship with effectiveness, measured as the use amount.

Advanced scientific computing provides partial support for Hypothesis 1. The allocation of Campus Champion computing resources demonstrates a positive association with the use amount. Regarding capacity, there is also support for Hypothesis 2 at the organizational level. If the institution to which the grant PI belongs does not have experience utilizing cyberinfrastructure resources (new to cyberinfrastructure), this organizational-level capacity challenge is negatively associated with the use amount. Meanwhile, the Carnegie15 classification for the institution, an indication of the highest research activity for doctoral universities, is positively associated with the use amount.

For Hypothesis 3, the results under advanced scientific computing provide partial empirical support. The findings indicate that the type of resource allocation matters. For example, both extreme and medium-size types of resources exhibit a statistically positive association with use amount. Supplemental transactions also demonstrate a positive association with use amount. In contrast, new and advanced types of transactions, an indication

of a lack of experience and of difficulty, exhibit a negative association with the use amount. Interestingly, the number of resources used exhibits a statistically significant negative relationship with use amount, controlling for all other variables.

The results from the three scientific fields collectively offer support for the three hypotheses while exhibiting nuances between the fields. Hypothesis 1, that equity effort is positively associated with effective outcomes, is partially supported by the results from chemistry and advanced scientific computing. For chemistry, a prior Campus Champion effort has a significant positive effect on the utilization amount. For advanced scientific computing, the resources allocated specifically for Campus Champion projects positively impact the use amount.

For the capacity hypothesis (Hypothesis 2), there is evidence from chemistry and advanced scientific computing supporting the positive association between capacity and effectiveness. For chemistry, the relevant capacity resides at the level of PIs. The PI's prior experience with cyberinfrastructure use and the PI's total previous cyberinfrastructure usage are significant predictors of effectiveness. In contrast, for advanced scientific computing, the statistically significant capacities are at the organizational level, including whether the institution (university or college) has any experience with cyberinfrastructure use and whether the institution is designated by Carnegie as a doctoral university with high research activities.

For Hypothesis 3 regarding socio-material coupling, the results support the relevance of such coupling for the effectiveness of cyberinfrastructure as a digital government platform. However, the hypothesis does not specify the direction of the association. For chemistry and advanced scientific computing, specific types and numbers of couplings exhibit a statistically significant relationship with use amount. For chemistry, large and extreme scales of resource allocation along with the renewal and supplemental types of transactions, are positively associated with use amount. In contrast, for advanced scientific computing, medium and extreme scales of resource allocation and the supplemental type of transaction are positively associated with use amount. The number of resources used demonstrates a significant positive relationship with the use amount for chemistry but a significant negative relationship with the use amount for advanced scientific computing.

5 Interpretation and Implications of the Results

The results for Hypothesis 1 suggest that equity effort supports the creation of effectiveness as a public value. The equity effort for the NSF cyberinfrastructure program has two dimensions. The first dimension is the Campus Champion program, which empowers and enables researchers to access and utilize cyberinfrastructure with the help of their local campus champion. The focus is on the researchers who are at a disadvantage in utilizing cyberinfrastructure resources. The Campus Champion program is also a national community of practice that leverages the knowledge and experiences of all champions [38]. The second dimension is the allocation of computing resources designated for campus champion purposes. These equity efforts demonstrate a positive impact on the use amount, controlling for the amount of initial allocation, capacity, and socio-material couplings. This statistically significant result suggests the specific and independent contribution of equity efforts to the effectiveness of cyberinfrastructure as a digital government platform in the context of many other influencing factors.

The positive relationship between equity effort and the effectiveness of cyberinfrastructure for advanced research computing as a digital government platform has implications for both theory and practice. This study contributes empirical evidence supporting the link between equity effort and effectiveness as one of the main mechanisms for public value creation [29]. For the literature on digital platform government, the results provide empirical evidence of the important role that equity plays in driving effectiveness, filling the gap in the literature on understanding effectiveness.

The importance of equity effort offers practical recommendations for enhancing the effectiveness of the cyberinfrastructure. The experience of equity efforts such as the Champion program suggests that initiatives for the entire digital government platform are productive. The findings also imply that a focus on creating a community

of campus champions with supporting resources yields a larger use amount. Digital platform government can incorporate similar equity efforts with the creation of a platform-wide community with members embedded in individual institutions to provide locally based support for accessing platform-wide resources.

The results on capacity suggest that capacity has a positive impact on the effectiveness of cyberinfrastructure as a digital government platform. Capacity resides at the level of PIs and the level of universities and institutions. At the PI level, being new to cyberinfrastructure implies a steep learning curve. Therefore, lack of experience is negatively associated with use amount. In contrast, the previous total use amount of cyberinfrastructure resources captures the overall knowledge and skill that a PI possesses. Thus, a past track record is a good predictor of the use of resources for a particular grant. At the institutional level, a lack of experience with cyberinfrastructure indicates a lack of institutional capacity to bridge the institution-specific research computing to the national cyberinfrastructure. On-campus advanced computing facilities and staff constitute important elements of institution-wide capacity. The institution-wide research capacity across disciplines also matters. As discussed in the data and method section, the Carnegie 15 designation (Doctoral Universities: Highest Research Activity) reflects the number and productivity of doctoral programs offered by a university or institute. The results suggest that high research capacity, as indicated by the Carnegie designation, translates into a high level of effectiveness measured by use amount.

The theoretical contribution of this finding is two-fold. First, it provides empirical evidence of the importance of capacity in driving performance, which is critical for the development of a theory of performance for digital government platforms. The existing literature on cyberinfrastructure that connects organizations and machines virtually identifies capacity as an important factor for effectiveness [32, 35, 66]. However, the previous literature lacks direct empirical evidence, which this study provides. Moreover, the findings also highlight the need to distinguish capacities at the individual level from those at the institutional level. Theoretical development in digital government platforms must pay attention to the distinction between levels and their respective capacities.

The practical implication of the findings on capacity is the need to develop an effective capacity-building strategy. Such a strategy needs to target assistance for the initial adoption and use of the national cyberinfrastructure resources. Initial adoption is the most significant barrier, but at the same time, it represents the biggest opportunity to increase effectiveness. Moreover, a capacity-building strategy must differentiate between PI-level and institution-level efforts to ensure effectiveness. For some fields of science, PI-level efforts are more impactful than institution-level efforts.

The importance of socio-material coupling is evident in the results on the associations among the type of resource allocation, the type of transaction, and the number of resources used. The type of resource allocation indicates the scale of the coupling between a PI's grant project and the type of computing resource utilized. The scale reflects the strength of socio-material coupling. The relationship between the type of resource and effectiveness implies that the scale of socio-material couplings matters. In addition, the type of transaction depicts the nature of the coupling, whether new or advanced, renewal or supplemental. New and advanced transactions suggest a high level of difficulty in coupling the PI and the resource.

In contrast, renewal and supplemental transactions suggest an extension of existing resources used and relative ease of coupling. These relationships between types of transaction and effectiveness collectively suggest that the ease of socio-material coupling promotes effectiveness. The number of resources used has a different relationship with use amount depending on the field of science. For chemistry, the set of codes for utilizing advanced computing resources may be mature and standard. Thus, a higher number of resources is helpful for use amount. In contrast, for advanced scientific computing, the codes are more experimental and varied. Therefore, navigating more resources becomes counterproductive for use amount.

The results on socio-material coupling provide empirical support for the importance of the material and the relevance of socio-material couplings in understanding cyberinfrastructure as a digital government platform. However, previous studies on socio-materiality [e.g., 9, 48] lack empirical validation of the mechanism through which coupling can increase the effectiveness of a collaborative digital government platform. Future research on

digital government platforms could, therefore, benefit from the explicit modeling of materials in the network of technologies and organizations, and of their coupling to understand performance. Moreover, the results suggest the relevance of both the scale and the nature of socio-material coupling for the effectiveness of cyberinfrastructure. Further theoretical development should therefore incorporate both socio-material dimensions.

The findings on socio-material coupling hold practical implications for the focus of cyberinfrastructure implementation. Program managers of cyberinfrastructure could consider optimizing the promotion and use of a particular resource to maximize effectiveness. For instance, the deployment of extreme resource allocation would benefit utilization more consistently than other types of resource allocation. Moreover, program managers could consider promoting the use of supplemental and renewal types of transactions to increase effectiveness.

The main explanations for the differences among disciplines in the specific equity effort, capacity levels, and applicable resource scale and transaction type are the maturity and variability of tools used to access cyberinfrastructure. Advanced scientific computing researchers are technologically accomplished but often have not made use of shared systems to conduct analyses and may need training on how to make use of national resources. In addition, the tools in this field are mostly experimental and at the early stage of development and are thus less mature and more variable. Due to the experimental and variable nature of the tools, equity effort directed at Campus Champion computing resource allocation rather than having a campus champion can make a positive impact on the use amount. Moreover, new and advanced types of transactions could constitute a significant barrier to utilization.

In contrast, most institutions have well-established chemistry departments with faculty that have a background in computational techniques. Graduate students are expected to develop computational competencies as part of their training process. The maturity of the computational techniques in the discipline of chemistry helps explain the differentiating effect of the knowledge and experience of PIs on their utilization of cyberinfrastructure. Moreover, the tools for utilizing cyberinfrastructure resources are relatively mature and standardized compared to those for advanced scientific computing. Therefore, chemists can better capitalize on extreme and large resource allocation as well as renewal and supplemental transactions than computer scientists.

In comparison with the other two fields, the field of genetics and nucleic acids is at the lower end of maturity and the higher end of variability in terms of accessing and using cyberinfrastructure resources. Many of the codes used in this field were individually built or created by a community of researchers. In addition, many of the analysis codes were developed outside of the high-performance computing area, and effective usage of high-performance computing resources in a shared context can be a challenge. Due to the continuing increase of data from faster sequencing and the diversity of subjects (microorganisms to humans and everything in between), standardization of codes can pose a challenge. The combination of low maturity and high variability in the tools for accessing cyberinfrastructure could explain the lack of a particular set of factors directly impacting the use amount.

The variations among disciplines in relevant equity effort, capacity level, and the type of socio-material coupling underscore the need to model the role of specific scientific fields for the theoretical development of cyberinfrastructure as a digital government platform. A generic theory of the effectiveness of cyberinfrastructure as a digital government platform is likely to neglect one of the most important differentiators. More specifically, theoretical development can benefit from close attention to the maturity and variability of the tools that access and utilize resources provided by cyberinfrastructure. In addition, the variations in the relevant level of capacity (individual vs. institutional) underscore the need to explore levels and the implications for effectiveness [7, 52].

The main practical implication is the need for a field-specific strategy and consideration of all three key factors for designing and implementing effective cyberinfrastructure as a digital government platform. Each scientific field has unique characteristics in the utilization of cyberinfrastructure resources. Moreover, a targeted effort could take into account the maturity and standardization of tools used for utilizing cyberinfrastructure. Variability across the scientific fields could also suggest efforts catering to specific fields of science to maximize impact.

6 Conclusions

Platform government is an increasingly important form of collaboration across individual, organizational, and sectoral boundaries in digital government. Cyberinfrastructure for advanced computing resources has gained salience in national efforts to increase competitiveness in scientific innovation. This study focuses on the US NSF's cyberinfrastructure program, which exemplifies the public mission of cyberinfrastructure in its pursuit of effectiveness in enabling the utilization of advanced computing resources. This study draws from the scholarship on digital government, digital platform government, cyberinfrastructure, and socio-materiality to develop a conceptual framework for the effectiveness of cyberinfrastructure as a digital government platform. This study hypothesizes positive impacts of equity effort, capacity, and socio-material coupling on effectiveness. The basis for data analysis is grant-level data from four data sources. The selected scientific fields represent high, medium, and low levels of effectiveness. The use of the Tweedie generalized least squares matches the distributional characteristics of the dependent variable.

The results from the three models collectively provide support for the importance of equity effort, capacity, and socio-material couplings for effectiveness. The findings on equity effort contribute to the understanding of its role in effective cyberinfrastructure as a digital government platform. The findings specifically indicate the importance of having a campus-specific support person as well as a national community behind campus-specific support to increase the impact of cyberinfrastructure as a digital government platform. The findings on capacity provide empirical evidence on the relevant type of capacity and the levels on which these capacities reside. The relevant types of capacity are prior experience with cyberinfrastructure and cumulative utilization amount. Depending on the field of science, the relevant capacity can reside at the level of PIs or the institutional level. This finding contributes to a nuanced understanding and application of the types and levels of capacity, which supports the development of a theory of effective digital government platforms.

The scale and type of socio-material couplings can also influence the effectiveness of cyberinfrastructure as a digital government platform. A larger scale is associated with a higher level of effectiveness. In addition, the types of couplings that match the characteristics of a discipline help increase effectiveness. The findings on the importance of socio-material coupling provide empirical validation of the need to explicitly model such couplings to advance the understanding of digital government platforms. Furthermore, these findings assist the managers of digital government platforms in identifying and strengthening salient couplings for effectiveness.

This study acknowledges several limitations and associated future research opportunities. First, this study did not explore the mechanisms through which equity efforts or the demographic characteristics of researchers can make a difference. Further understanding of these equity-enhancing mechanisms and demographic characteristics can help improve the theory and practice of linking equity to effectiveness. Second, due to scope, the interplays between capacities at levels were not studied. A future study of this topic can shed light on how capacity at one level can affect capacities at other levels to enhance the development of a multi-level capacity-building theory. Lastly, the emergence of the maturity and variability of cyberinfrastructure tools as explanations for differences between fields requires further rigorous empirical testing. Future research can investigate more fields to determine if these explanations have validity.

Acknowledgments

The authors acknowledge the research assistance from Andrew Burk.

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Received 11 May 2023; revised 22 January 2025; accepted 1 June 2025